# Final Technical Report

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| Award Number: | 1434-HQ-97-GR-03080 |
| Applicant: | The Regents of the University of California<br>Sponsored Projects Office<br>Room 336 Sproul Hall<br>Berkeley, CA 94720 |
| Principal Investigator(s): | Dr. Patrick Williams<br>Berkeley Seismological Laboratory<br>University of California at Berkeley<br>Berkeley, CA 94720-4760<br>Telephone Number: (510) 643-4806<br>FAX Number: (510) 643-5811<br>Email Address: pat@seismo.berkeley.edu |
| Project Title: | Hayward Fault Slip Vector and Rate Constraints at Berkeley: Reinterpretations of EB Landforms and Tectonic Hazards |
| Element Designation: | I, II |

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 1434-HQ-97-GR-03080. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

# Non-Technical Project Summary

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| Project Title: | Hayward Fault Slip Vector and Rate Constraints at Berkeley: Reinterpretation of East Bay Landforms and Tectonic Hazards |
| Applicant | The Regents of the University of California, Sponsored Projects Office<br>Room 336 Sproul Hall, Berkeley, CA 94720-5940 |
| Principal Investigator(s): | Dr. Patrick L. Williams, Berkeley Seismological Laboratory, University of California, Berkeley, CA, 94720-4760<br>Telephone Number: (510) 486- 7156<br>FAX Number: (510) 486-4159<br>Email Address: pat@seismo.berkeley.edu |
| Element Designation: | I, II |

Offset and abandoned channels of Strawberry Creek record the vertical and lateral motions of the northern Hayward fault at Berkeley. The fault has displaced the modern stream course by 335±30 m (1100 ft) in a lateral sense. Prominent beheaded channels of Strawberry Creek are offset 580 m (1900 ft) and 730 m (2400 ft). The age of beheaded stream deposits, obtained from a construction exposure across the youngest paleochannel, is 32,200±360 radiocarbon years. This is a minimum initiation age for the modern (335 m) stream offset, and provides a direct record of the long-term-average slip rate of the Hayward fault, 10.4±1 mm/yr. This rate, if steady over a longer period, indicates that the Hearst paleochannel was beheaded about 55,000 years ago. The 350 m width across which the Strawberry Creek offset is interpretted extends well beyond the fault's local complexity, and provides a high confidence record of the fault's late Quaternary slip rate. This long term slip rate enables more robust forecasts of future rupture hazard. The rate is 10-20% higher than previous geological determinations of slip rate, indicating an accordant increase in probabilistic earthquake hazard estimates for the northern Hayward fault.

## Abstract

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Author: Dr. Patrick L. Williams, Berkeley Seismological Laboratory, University of California, Berkeley, CA, 94720-4760
Telephone Number: (510) 486- 7156
FAX Number: (510) 486-4159
Email Address: pat@seismo.berkeley.edu

The displaced channels of the Strawberry Creek drainage define large-scale reference lines from which a high-resolution long-term Hayward fault slip rate can be recovered. Active and former channels of the Creek are offset across the northern Hayward fault at Berkeley, California. The fault has displaced the modern stream course by 335±30 m (1100 ft) in a right-lateral sense. Prominent beheaded channels of Strawberry Creek are offset 580 m (1900 ft) and 730 m (2400 ft). The radiocarbon age of beheaded stream deposits, obtained from a construction exposure across the youngest paleochannel, is 32,200±360 radiocarbon years. This is a minimum initiation age for the modern (335 m) stream offset, and provides a direct record of the long-term-average slip rate of the Hayward fault, 10.4±1 mm/yr. This rate, if steady over a longer period, indicates that the Hearst paleochannel was beheaded about 55,000 years ago. The 350 m width across which the Strawberry Creek offset is interpretted extends well beyond the fault's local complexity, and provides a high confidence record of the fault's late Quaternary slip rate. This long term slip rate enables more robust forecasts of future rupture hazard. The rate is 10-20% higher than previous geological determinations of slip rate, indicating an accordant increase in probabilistic earthquake hazard estimates for the northern Hayward fault.

## Final Technical Report

### *Introduction*

Accurate determination of the total slip rate of the Hayward fault has remained an ellusive goal. The Hayward is a major strand of the San Andreas fault system, bounding the East Bay Hills province the California Coast Range. Previous geological studies directed at determination of a Hayward slip rate rely on observations of offset alluvial fan features that may not span the entire fault zone (Lienkaemper and Borchardt, 1996). Additional direct evidence of the total slip rate of the fault comes from observation of a 9-mm/yr creep rate at Warm Springs (Lienkaemper *et al.*, 1991). These observations were utilized for a probabilistic hazard calculation by the Working Group on California Earthquake Probabilities (WGCEP, 1990). The WGCEP adopted a 9±2–mm/yr total slip rate. Geodetic data can be used to evaluate the short-term slip rate across the entire plate boundary in the San Francisco Bay area, but cannot distinguish the slip rates of individual faults (Lisowski *et al.*, 1991). Ironically, the fluvial landforms of the University of California's original campus provide key evidence of the Hayward fault's long-term kinematics. This is not simply a fluke, as a criteria for the site was a reliable year-round water supply (Strawberry Creek). Major features of the campus physiography resulted from large-scale, long-term stream offset. In this paper, the large offsets of Strawberry Creek and its paleochannels are evaluated to recover a long-term Hayward fault slip

Strawberry Creek landforms have been heavily rate. modified by construction that obscures key field relationships, but their elements are preserved in detailed maps, relic landforms, prior geological studies, and buried stratigraphic evidence. Andrew Lawson's mapping of the Hayward fault through Berkeley and Oakland xwas initially published in the Carnegie Institute report on the 1906 San Francisco earthquake (Lawson *et al.*, 1908; Atlas Map 5). The lateral character of Hayward fault motion was alluded to by Andrew Lawson in his San Francisco Folio, which illustrates a good understanding of the fault's relationship to stream offset and deflection, including the lateral offsets of Strawberry and Claremont Creeks (e.g. Fig. 1). Richard Russell (1926) provided the first explicit descriptions of progressive right-lateral stream and fan offsets along the fault. These were accompanied by his remarkable observation that active right-lateral motion characterized both the Hayward fault and the San Andreas fault and was pervasive through the central California Coast Ranges. Russell also indicated that the Berkeley Hills highlands were not simply associated with vertical uplift on the eastern side of the fault, as the fault was not consistently located at the base of the hills, but extended into the hills in several locations. John Buwalda (1929) made key observations of the geomorphology and stratigraphy of lateral offset at the U.C. Berkeley campus before and during construction of the California Memorial Stadium in 1923, and described the ~350-m right-lateral offset of Strawberry Creek.

Despite severe landscape modifications at the site, a rich archive of maps and geological studies of the U.C. Berkeley site have provided an ample context for this analysis of the rate of long-term Hayward fault motion. Maps that have enabled this study are highlighted by a detailed plane table (topographic) map of the campus compiled in 1897 (Fig. 2). The map includes the whole campus area and extends eastward across the Hayward fault zone. Other notable topographic maps were made across the Strawberry Creek site between the dates 1908 and 1940. These maps are highly detailed, and are characterized by a 5-ft. (1.524-m) contour interval. The existence of several generations of topographic mapping across the Strawberry Creek offset allow differences of detail and style to be evaluated and distinguished from actual landscape modification. Less detailed topographic mapping of the local region includes a mapsheet of a portion of the western Berkeley Hills (see inset to Fig. 1, contour interval = 10 ft./3.048 m; Otis, 1900; Lawson and Palache, 1902; ); the Concord, California Quadrangle Sheet (1915, contour interval = 25 ft./7.62 m; and an unattributed campus map published by the U.C. Berkeley Associated Students in 1923 (see Fig. 1, contour interval = 20 ft./6.096 m). These maps are useful for more general interpretation of the original landscape of Strawberry Canyon, including stream profile, and for compilation of the original fault zone landscape across a wider region.

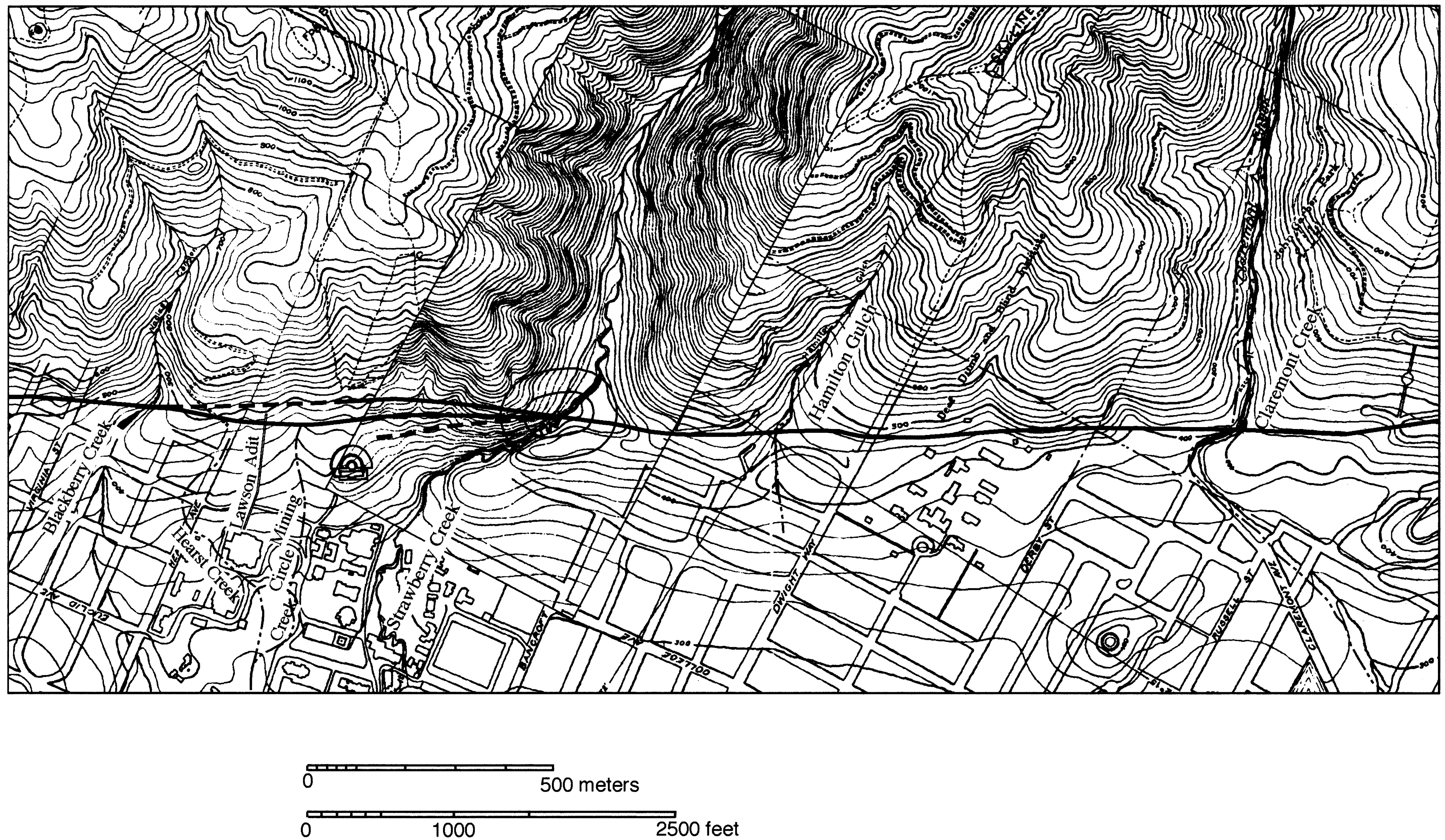


**Figure 1**. Topographic map in the vicinity of the Hayward fault zone, southeast section of Berkeley, modified from Associated Students Map circa 1923. Note the abrupt increase of slope at the fault-line and the right-lateral offset of Claremont, Hamilton, Strawberry and Blackberry Creeks by the Hayward fault. Inset from Otis, (1900) illustrates the pre-construction mapping of Strawberry Creek area. Note the prominent shutter ridge that has been displaced 1100 laterally in front of Strawberry Canyon. Contour interval = 20 ft (contour interval of Otis map is 10').

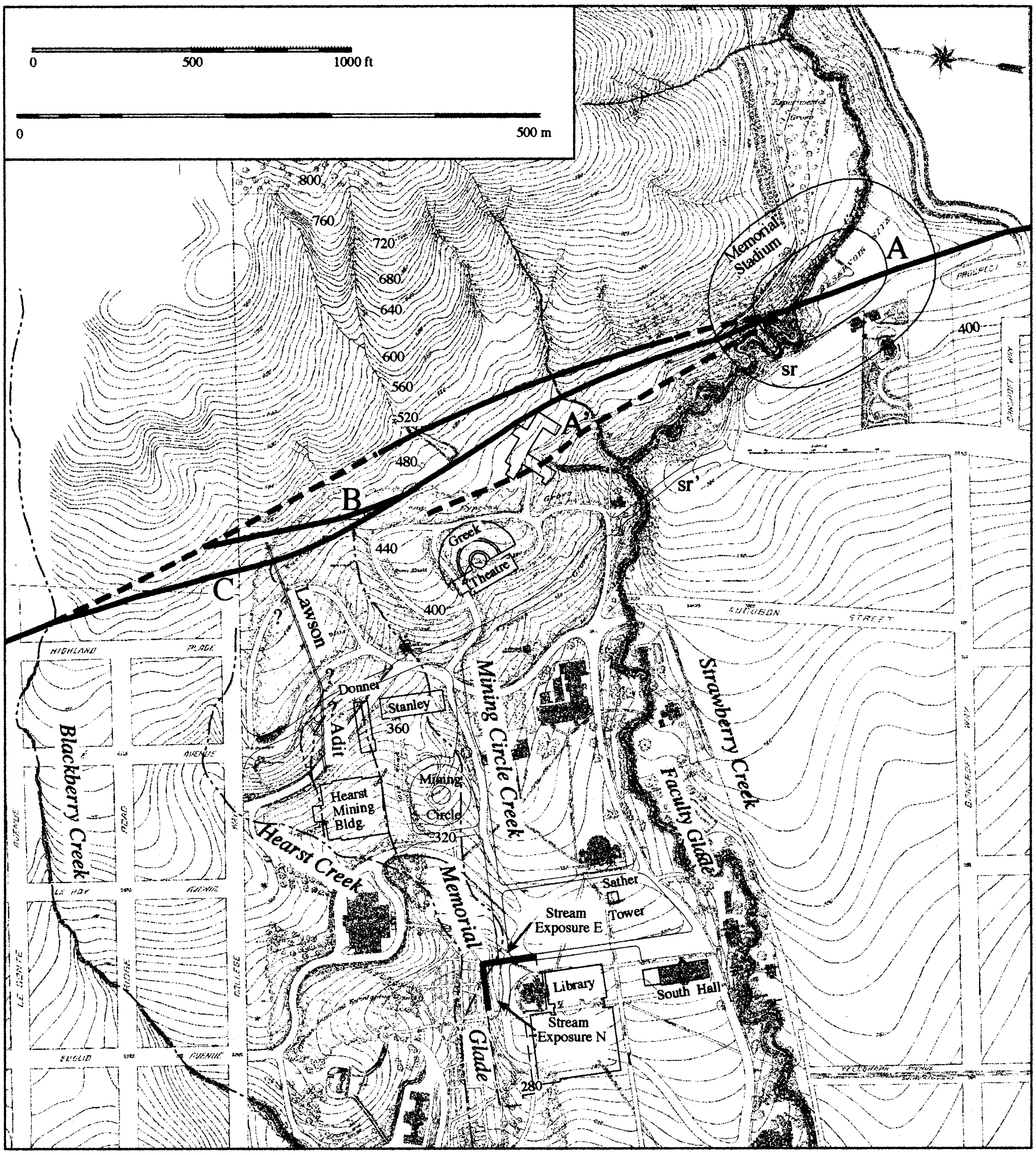


**Figure 2.** Topography of the east campus area, UC Berkeley (from King, 1897). 1897 structures are solid. Modern streets and buildings outlined for reference. Where the fault trace is drawn as a solid line, the location has been determined from multiple lines of evidence, and the fault's location is deemed reliable. Major fault-related landforms include: A-A': 335-m-offset of active Strawberry Creek channel; A-B: 580-m-offset of Mining Circle paleochannel; A-C: 730-m-offset of Hearst paleochannel. Sr: primary shutter ridge; Sr': remnant shutter ridge, (at positions Sr and Sr' the width of the ridge has been reduced by erosion); Contour interval is 4 ft below 400 ft and 8 ft above. Note unnamed channels interpretted from exposures in Lawson Adit and Donner Hall. The Mining Circle channel was exposed in the 1992 Library excavation.

***Lateral offset of Strawberry Creek***
Motion of the Hayward fault has displaced the modern, active course of Strawberry Creek, a large competent stream, by 335 m (1100 ft) in a right-lateral sense of motion (Fig. **2**).

The creek offset was described in detail by Buwalda (1929) who noted that the stream course was deflected “approximately 1200 ft” by a fault-bordering ridge of colluvial deposits (a shutter ridge). The ridge extends for a length of about 450 m (1500 ft), and ranges in height from 5 to 20 m. It bounds a fault-line valley to the south of Strawberry Canyon, and comprises the western bank of the stream valley along the length of the modern offset. At positions sr and sr’ (**Fig. 2.**) the width of the ridge has been reduced by progressive erosion of the stream’s western bank.

Buwalda (1929) described the stratigraphy of the ridge from excavations during construction of Memorial Stadium. He noted that clasts were predominantly angular, and that serpentine fragments were common. Serpentine is absent in the Strawberry Creek drainage, but outcrops in the watershed of Hamilton Gulch, a small steep drainage 400 m to the southeast of Strawberry Canyon (**Fig. 1**). The presence of Serpentine in the ridge, and lack of rounding of the shutter ridge gravels identify them as originating from Hamilton Gulch. Buwalda also noted that the modern mouth of Hamilton Gulch is approximately level with the crest of the shutter ridge deposits, indicating the vector of slip along this stretch of the fault had been close to horizontal.

***Morphology of the Strawberry Creek channels***
To the west and downslope of the Hayward fault at U.C. Berkeley, prominent beheaded channels of Strawberry Creek are offset 580 m (1900 ft) and 730 m (2400 ft). The 580-m-offset channel is here referred to as the "Mining Circle channel." The 730-m-offset channel is termed the “Hearst channel.” On the basis of landform inspection, the Hearst channel is essentially similar in form to the Mining Circle channel, and both channels are greatly overfit for their present drainage areas. This alone strongly infers a Strawberry Creek origin for these channels. Williams and Hosokawa (1992) argued that the present offset of Strawberry Creek accumulated subsequent to abandonment of the Mining Circle channel.

Strawberry Creek and its paleochannels are analogous to landforms of the Wallace Creek site, where a Holocene slip rate was established for the San Andreas fault (Wallace, 1975; Sieh and Jahns, 1984). As at Wallace Creek, the paleochannels of Strawberry Creek provide relationships from which a long-term lateral slip rate can be determined. Profiles of the Strawberry, Mining Circle, and Hearst channels are presented in **Fig. 3**. Early in this study, a presumption was made that the Strawberry Canyon profile (above the fault) would fit smoothly with the relict Hearst and Mining Circle profiles below the fault, and would thus establish their association. This is *not* the case. The two beheaded channels are significantly steeper than the active channel of Strawberry Creek, particularly in their upper sections close to the Hayward fault. It appeared that these might not be paleo-channels of Strawberry Creek after all. Note, however the very similar profiles of the Hearst and Mining Circle channels, indicating that these two channels have essentially identical histories.

Stratigraphic evidence, described in the following section, substantiates the paleo-channel interpretation. Why then are the Hearst and Mining Circle profiles so much steeper than the Strawberry channel, despite their common origin as drainages of Strawberry Canyon? Buwalda (1929) suggested that the channels had been steepened to their present attitude by tectonic tilting. Unless the tilting postdates the younger Mining Circle Channel, however, the significantly older Hearst channel should be tilted more steeply than the Mining Circle channel. Inspection of Figure 3 indicates that is not the case. Environmental factors may contribute to the substantially different profiles of Strawberry Creek and its paleochannels. The two paleo-channels were abandoned about 30 and 60 thousand years before present, when sea level was 50-100 m below present (e.g. Bloom *et al.*, 1974). This lowered base-level favored steepened profiles to achieve an equilibrium stream profile. Response to elevated sea-level is suggested in apparent fill of the Strawberry Creek stream valley, for example in Faculty Glade, Fig. 2). Stream responses to sea level change may thus be fortuitously preserved by the tectonic beheading of Strawberry Creek channels.

1. The below-fault profile is steepest just beyond the fault offset and flattens exponentially towards base-level. Strawberry Creek's modern profile is graded to interglacial sea level, producing a flatter profile, and filling glacial-era valleys.

The steepness of the lower portions of the paleochannels is remarkable. This steepness is presumed to result from multiple factors: a) evolution of the drainages during late Wisconsin glacially-lowered sea level; b) higher late Wisconsin severe-storm frequency, resulting in greater stream capacity ; c) inheritance of a deeply cut bedrock valley (Memorial Glade, Figure 2); d) possible tectonic uplift or tilting in the fault zone.

Major features of the Strawberry Creek profile are attributed to tectonic and climatic factors favoring aggradation. Aggradation within Strawberry Canyon results from alluvial ponding behind the shutter ridge. The tectonically-lengthened segment interrupts the stream profile. Progressive stream offset within the shutter ridge section causes the profile to lengthen and flatten, promoting aggradation. Near-fault alluvial deposits within Lawson Adit lie 20 to 30 feet lower than the modern stream profile, indicating minimum profile aggradation at the the canyon mouth of this amount. A wide fluvial terrace below the shutter ridge, "Faculty Glade" (Figure 2), also indicates substantial flattening of the profile. This aggradation probably resulted from Holocene rise of base-level and drop in stream discharge.

### *Stratigraphy of the beheaded channels of Strawberry Creek*

Stratigraphic evidence provides the strongest support of the Strawberry Creek origin of the beheaded stream channels at U.C. Berkeley. Stratigraphic relationships have been documented in various exposures in the area. The association of the beheaded stream channels with Strawberry Creek is supported by the provenance of gravels exposed in excavations during the 1992 expansion of UC Berkeley Libraries in the central campus. The library was extended into a broad swale near the confluence of the Hearst and Mining Circle channels (**Fig. 2**). A channel, cut into bedrock,was exposed in the excavation. The channel is filled with silty sand, sandy silt, and lenses of well-sorted pebbly sand and sandy pebble-gravel. Clasts of Claremont Chert are common in the gravels. The presence of chert and volcanic pebbles are characteristic indicators of Strawberry Creek alluvium in the campus area. The absence of chert or volcanic rock outcrops in the hillslope above the U.C. Berkeley campus, and the abundance of these rocks in the Strawberry Creek watershed identifies these deposits as originating from Strawberry Canyon. A second exposure of rocks of the Mining Circle channel was made during studies of the so-called Louderback fault trace in geotechnical studies for the Foothill Housing project (Korbay , 1988). The gravels were exposed 100 m northwest of the Greek Theatre (**Fig. 2**). These gravels are also stream deposited and containing clasts of chert.

Three stratigraphic channels were described in the Lawson Adit by George Louderback (unpublished field notes, 1938-1941). Chert was found in the gravels associated with the Lawson Adit channels (Fig. 2). The Adit is a 232 m (760-foot) shaft excavated eastward from a portal near the Hearst School of Mines building and extending to the fault zone (**Fig. 2**). The Adit was begun in about 1915 as a teaching laboratory for the School of Mines. Buwalda (1929) examined the gravels of the outer two channels, and described them as similar to the modern deposits of Strawberry Creek, i.e. comprised primarily of rounded clasts of sandstone and basalt and shale. In 1939 the Adit was extended 155 m (510 ft) into the fault zone under the direction of Professor Louderback. The purpose of the excavation was to evaluate the location of the Hayward fault. The Adit was probably the first and only geotechnical excavation of its kind for direct study of active faulting. Access is presently limited to the outer 80 m (270 ft) of the Adit. The easternmost gravel in the Adit extends to 646 ft and projects near to the Hearst paleochannel in plan view (**Fig. 2**). The truncation of the easternmost alluvium was taken Louderback to identify a primary trace of the Hayward fault. Clasts were described in the Adit by George Louderback (unpublished field notes, 1940-41) and are noted to be chert-bearing. The western two gravel deposits (located at 130 to 170 ft and 220 to 400 ft) are associated with channels intermediate between the Mining Circle and Hearst paleochannels in position and age. These intermediate Lawson Adit gravels have no associated fluvial landforms, indicating that the former channels are entirely covered by slope debris, with a likely landslide component. The morphology of the older Hearst channel was not subdued, apparently because it had moved too far along the fault to be in the path of thick slope deposits, and because it was protected from subsequent deposition by an intervening ridge (capped by Founders Rock, Figure 2). Buwalda (1929) studied the two western Adit gravels and associated them with fault offset, arguing that sorting, wear and provenance of the gravels tied them uniquely to Strawberry Canyon, 700 m to the south. The association of both the Mining Circle and Hearst paleochannels with the Strawberry Canyon drainage is thus strongly supported by stratigraphic evidence.

### *Constraints on Strawberry Creek offset*

Determining a long term slip rate from the length and antiquity of the Strawberry Creek offset assumes a simple evolution of this landform. In capturing flow from the Mining Circle channel, the

Strawberry Canyon (**Fig. 3**). This primary assumption, while reasonable, contains some uncertainty. Large offset of an active stream produces a lengthened and flattened profile, analogous to that exhibited by the modern Strawberry Creek profile, and causing it to become increasingly vulnerable to capture. Capture occurs by headward erosion across the shutter ridge or by translation of an inherited low in front of the active channel (**Fig. 4**). As an example, in the original configuration, as the Hearst channel moved in front of Blackberry Creek it would have captured that stream (Fig. 2). Similarly, former channels of Hamilton Gulch may have captured Strawberry Creek. Capture near the axis of the Strawberry Canyon is favored over other configurations (e.g. Sieh and Jahns, 1984; Lienkaemper and Borchardt, 1996).

The fault intercepts of channel features projected from within Strawberry Canyon and along the nose of the shutter ridge indicate a total creek displacement of slightly more than 335 m. Uncertainties of one and two standard deviations are informally assigned to this interpretation as follows. Projections of 60-80 m are made from bank features defining the downstream (western) side of the stream offset to the prominent middle fault trace. The minimum bound is felt to be quite firm, since the nose of the shutter ridge is steep and slightly concave, indicating some ridge erosion and channel migration to the southeast. The maximum offset length is defined by a fault-perpendicular contours and low terrace risers that are traced for 60 m along the north and south banks (**Fig. 3**). One sigma (1s) uncertainty indicated by these projections is ±11 m and the 2s uncertainty is assigned at ±22m. These error bounds are illustrated in Figures 2 and 3, and they are judged to be conservative values. To account for uncertainty in the 60-80 m extrapolation to the fault, an error multiplier of 2.0 is applied, bringing the 1s and 2s variance to ±22 and ±44 m, respectively. Larger offsets are believed more probable, since channels may be buried within the subdued topography to the north of the shutter ridge, but shutter ridge preservation negates smaller displacements.

The south bank of Strawberry Canyon to the east of the fault is strikingly linear, and projects 40 m to the fault line. The projection is further constrained by a canyon-parallel contour that extends to the fault on the stadium grading plan (Fig. 3). Geomorphic features along the northern bank of the canyon are subdued and must be projected 90 m to the fault. The modern, low gradient channel is not cleanly offset at the fault, but bends gradually to the northwest over a broad arc. At the time of stream capture, however, the gradient of Strawberry Creek was high, and a straight channel was favored. Abundant evidence supports an initial steep and straight Strawberry Creek channel: (1) the straightness of Strawberry Canyon; (2) fill subsequent to capture has produced 60-m-broad fllod plain in lower Strawberry Canyon (Fig. 2); (3) the geometry of alluvial ponding in Canyon mouth indicates that the channel was 10 to 15 m deeper at the time of its capture; (4) channel remnants preserved on the flood plain identify former channel alignments 3) (3) a 40- to 80-m-wide valley floor is located along Strawberry Creek below the shutter ridge and expresses the 5-10 m fill of this section of the creek; (4) the very steep profiles of the Mining Circle and Hearst channels support an initial steep and straight slope of Strawberry Creek, since these channels were all formed during an equivalent (glacial) climatic regime; (5) stream-rounded cobbles and small boulders (to 30 cm diameter) are common in the ancient Strawberry Creek deposits mapped in Lawson Adit, and these are indicative of steep glacial-era stream gradient and high stream capacity; (6) except where deflected by fault and bedrock features, other local streams exhibit linear valleys (**Fig. 1**).

Fault intercepts from the northern and southern sides of Strawberry Canyon span ±10 m at the informal (1s) confidence level, and the higher (2s) uncertainty estimate is ±20 m. An error multiplier of 2.0 is again applied to account for uncertainty in the projections, yielding a 1s variance of 20 m and a 2s of 40 m.

Propagating the 1s uncertainties (±22 m and ±20 m) by the method of root-mean-squares (rms), $(X_{NW}^2 + X_{SE}^2)^{1/2} = X_{RMS}$, indicates a cummulative uncertainty of ±30 m. The 2s uncertainties, ±44 and ±40 m, yield an rms uncertainty of ±60 m, but it is this papers assertion that the displacement of Strawberry Creek is conservatively reported as 335±30 m.

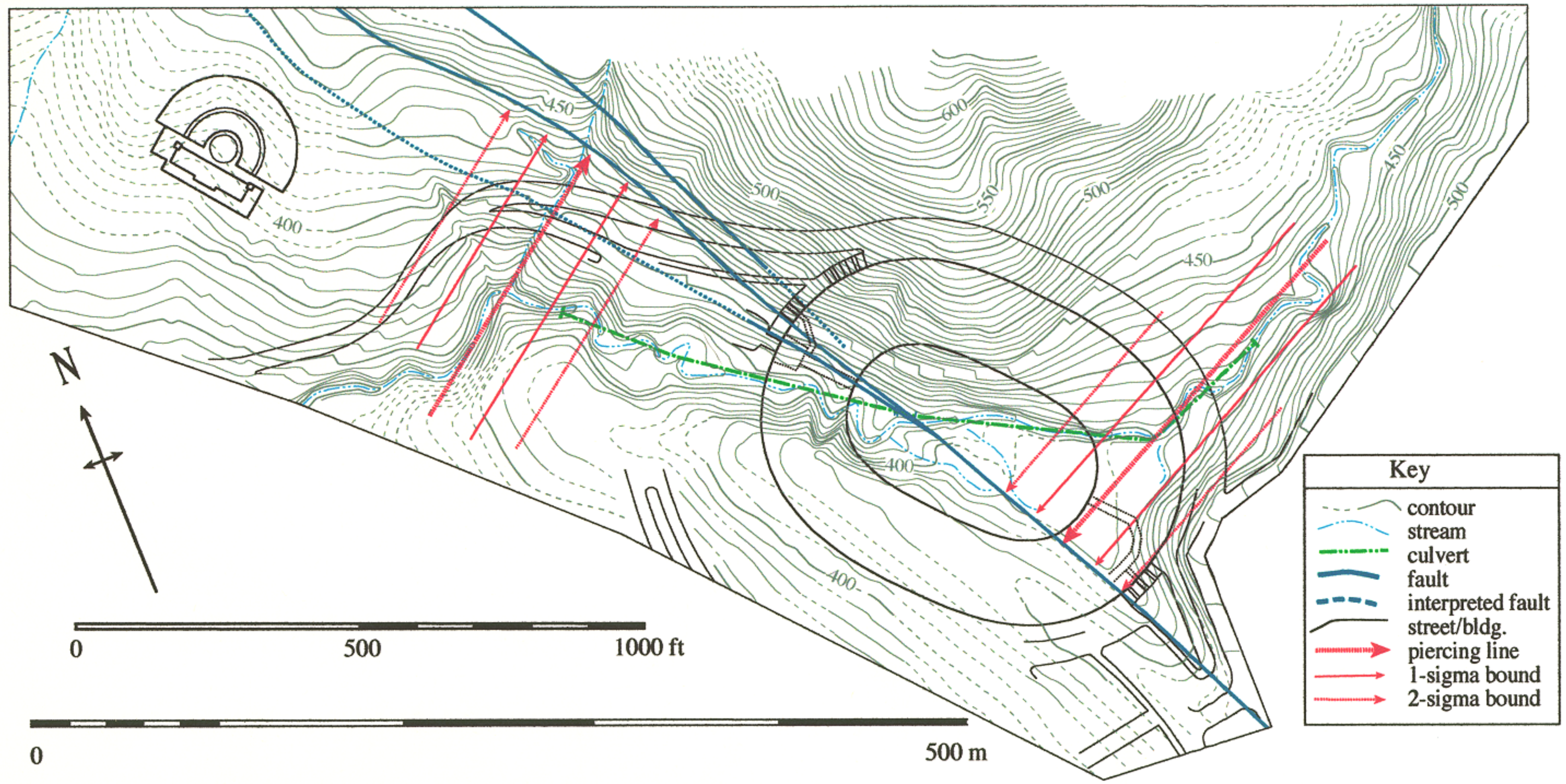


Figure 3. Detailed map of Strawberry Creek offset. Contour interval 5'. Solid lines are from the 1922 Memorial Stadium Commission survey; dashed lines are interpolated from King (1897). Intercept projected at nose of shutter ridge is a minimum bound since the ridge nose is steep andconcave, indicating erosion of the southern bank. Bounds of ±25 and ±50 m are illustrated. The Strawberry Canyon axis projects to the fault along the central arrow and ±20 and 40 m bounds are illustrated. Beheaded channel segments across ponded alluvium at the canyon mouth indicate rapid sedimentation and channel migration. At capture, the primary channel is assumed to have cut straight to the canyon. The linear south wall of Strawberry Canyon thus closely limits the maximum offset. The fault-line valley south of stadium is a primary tectonic feature with little fluvial modification. Roads are circa 1923.

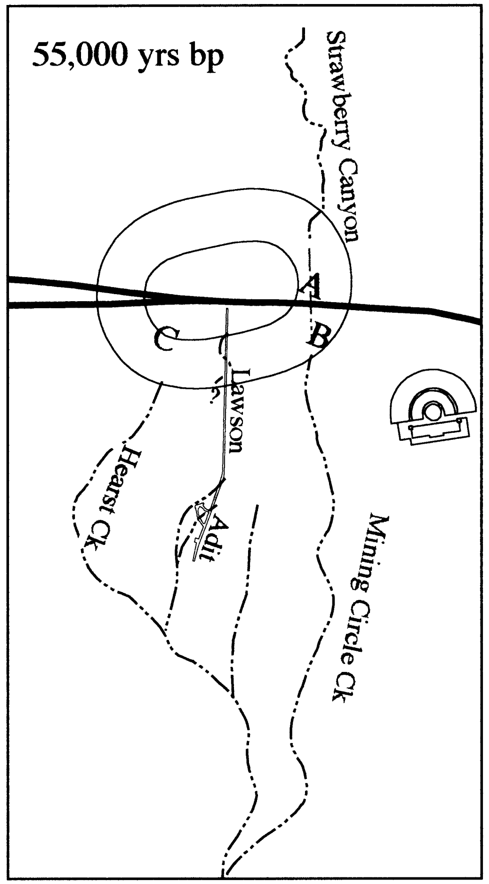


**Figure 4a.** Restoration of 580 m offset of Mining Circle Creek yields stream geometry of ca. 55,000 years before present. Stadium and Canyon stream segment held fixed. 60-80 m spacing of Hearst and Lawson Adit channels indicate frequent occurrences of stream capture.

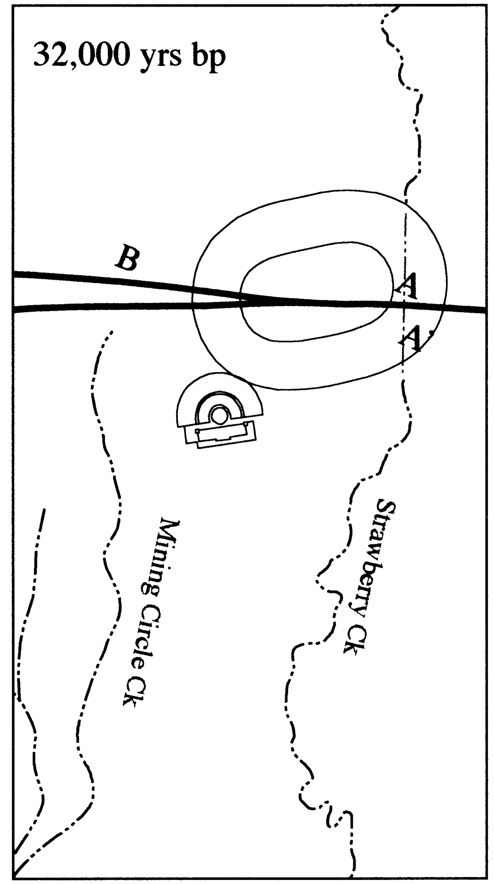


**Figure 4b.** Restoration of 335 m Strawberry Creek offset yields stream geometry of 32,000 years before present. Stadium and Canyon stream segment held fixed. Mining Circle channel was beheaded after about 245 m of offset.

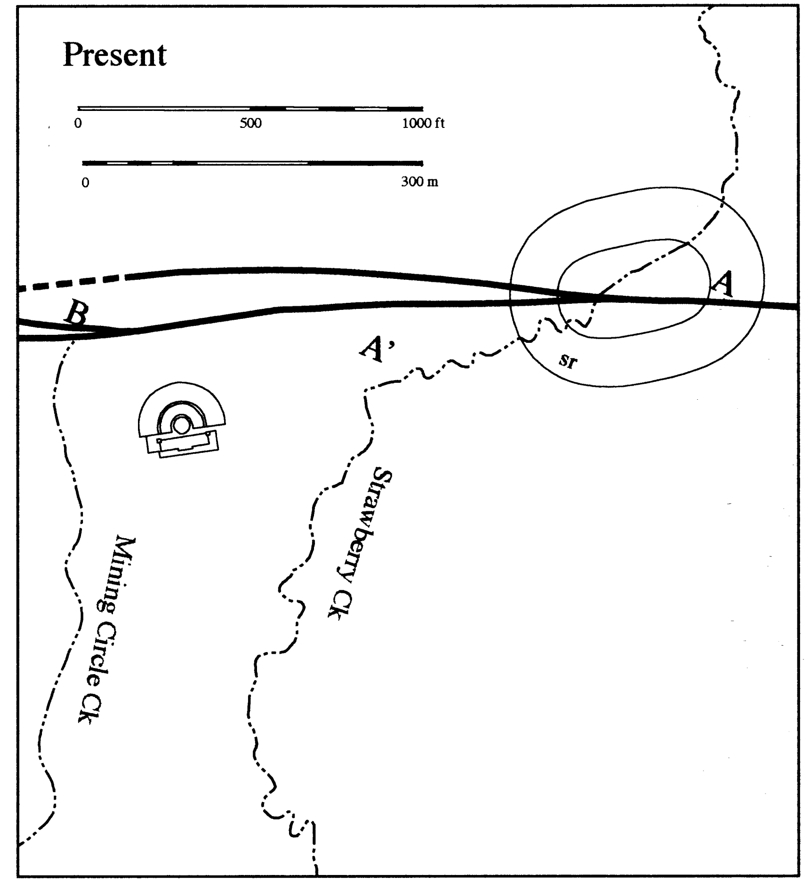


**Figure 4c.** Modern geometry of Strawberry Creek and Mining Circle channels. Present offset of Strawberry Creek is about 335 m.

***Mapping of the Hayward fault location near Strawberry Creek***

Reliable mapping of the fault's location serves to improve constraints for the slip rate evaluation at Strawberry Creek, and improves confidence that the entire fault zone is bounded by the offset markers. The fault has been mapped through the Berkeley area in several studies. Agreement about the fault's location is quite good to the south of the Berkeley campus. Within the campus however, from Strawberry Canyon northward, several fault trends are mapped, with marked disagreement among various investigators (e.g. Radbruch-Hall 1974; Smith 1980a, 1980b; Dibblee, 1980; Bergman and Korbay, 1988; Korbay, 1988; Lienkaemper, 1992; Crane, 1995; Williams, 1995). The disagreement is in part the result of real increase of fault zone complexity to the north of Strawberry Canyon (Figure 1). The complexity results primarily from a 60-m-wide right-stepping discontinuity of the fault trace. Resolving of the fault location is not the principal focus of this study, but is used to make the best estimates of total stream offset **Figures 1, 2 and 3** compile evidence of the locations of primary fault traces. Within the campus area two prominent fault traces are expressed by landforms, fault exposures, and distress to built structures. Most geomorphic expressions of the fault have been removed by development, and by the natural processes of landsliding and erosion. Some clear expressions of the fault remain, however, and essential geomorphic evidence of the fault's location has been recovered from large scale mapping of the site compiled in 1897 and 1922 (**Fig. 2 and 3**). Before construction the fault was expressed by a linear, northwest-trending zone of fault-related landforms. The offset of drainages by the Hayward fault provides primary evidence of fault location. In addition to Strawberry Creek and its paleochannels, the channel of Blackberry Creek is offset 60 m (190 ft) by the fault (Fig. 2). Between these two creeks, fault scarps, fault line valleys and stream offsets locate fault traces.

In addition to fault locations interpreted from ancient landforms, direct exposures of the shear zone have been mapped in a number of geotechnical investigations, during construction, and within the Lawson Adit (Professor George Louderback, unpublished field notes 1939-1941; Bergman and Korbay, 1988; Korbay, 1988; Williams and Hosokawa, 1992).

The phenomena of fault creep and the attendant distress of built features was also utilized in mapping the fault. A number of buildings in the campus area have been offset. Most notably, 37 cm of fault motion has accumulated across the California Memorial Stadium since its construction in 1923. Fault motion is expressed as distress of interior and exterior walls and joints, and is particularly apparent in the offset of an expansion joint along the stadium's southern rim.

***Abandonment age and slip rate determination***

The determination of a long term Hayward fault slip rate required recovery of the abandonment age of the Mining Circle channel. The Mining Circle channel was exposed during recent construction at Doe Library. Good exposures of the buried channel deposits are required to distinguish between fluvial and colluvial materials. The channel is cut in Franciscan bedrock at the Doe Library exposure, and channel-filling sediments are predominantly silty-sandy colluvium. The dominance of fine-grained material in the channels is indicative that the fill deposits date from post-abandonment time. Charcoal was extracted from the bottom of the colluvial section. The age of charcoal from these samples is 32,200±360 (1s) radiocarbon years. This age marks the initiation of the modern (335m) stream offset, and provides a direct record of the long-term-average slip rate (V) of the Hayward fault, by solving $V = X/T$ where $X=335\pm32.5$ m and $T=32{,}200\pm360$ yrs, resulting in a mean rate of 10.4 mm/yr. The 1s age uncertainty is 1%, while the displacement uncertainty is 9.5%. Uncertainty in slip rate is evaluated by propagation of the age uncertainty ($E_t$) and offset uncertainty ($E_d$).

**Equation 1**

$$E_{d/t} = \left\{ (E_d/T)^2 + \left(\frac{D * E_t}{T^2}\right)^2 \right\}^{1/2}$$

yielding 10.4±1.0 mm/yr (1s) and 10.4±2.0 mm/yr (2s). The 10.4 mm/yr rate, if steady over a longer period, indicates that the Hearst paleochannel was beheaded about 55,000 years ago, near the practical limit of radiocarbon dating.

***Slip rate influence on recurrence interval***

Lienkaemper and Borchardt (1996) determined slip rates of 8±0.7 mm/yr. over 8,300 years and 9.2±1.3 mm/yr. over 4,600 years from offset channels along the southern Hayward fault. Hayward fault creep rates peak at 9 mm/yr. near the south end of the fault (Lienkaemper et al., 1991). WGCEP (1990) derived a 9±2 mm/yr. slip rate from these values and determined a 167±67 year recurrence interval for 1.5 m ruptures of the Hayward fault. Reduced uncertainty of slip rate greatly improves the confidence of estimates of fault recurrence behavior. The power of a better resolved long-term Hayward fault slip rate to effect earthquake hazard calculations is illustrated as follows: The 9±2 mm/yr. slip generates a recurrence interval of 235±50 years for a two m rupture, and 350±80 years for a three meter rupture (Table 1).

Entering the revised slip rate into this approach indicates a mean recurrence interval of 195±20 years for a two meter event and 290±30 years for a three meter event (Table 1). The reduced rate uncertainty reduces the overall uncertainty in rupture hazard forecasts. In addition to the increase of geologically determined rate, strong evidence has been developed that the elapsed recurrence interval is longer than previously thought (from 162 to ≥222 years, Toppozada and Borchardt, 1998). Also, geodetic evidence has been developed that the 1868 Hayward fault rupture extended into north Oakland (Yu and Segall, 1996). The influence of these revisions of rate, elapsed quiescence, and rupture length on future rupture of the northern Hayward fault is complex. The longer period of quiescence and increase of the geologically-determined slip rate act in concert to advance hazard, while the greater length of the "1868 segment " could act to reduce the fault area (and moment magnitude) of a future northern Hayward rupture. These are competing factors, but their trend indicates a significantly higher earthquake hazard from the northern Hayward fault than was previously realized.

Table 1. Recurrence period as a function of rate and displacement

| | displacement (m)[1] | | | | |
|---|---|---|---|---|---|
| rate (mm/yr) | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
| 8.0±0.7 [2] | 125±10 | 189±17 | 252±22 | 315±28 | 378±33 |
| 9.0±2 [3] | 117±25 | 175±39 | 234±52 | 292±65 | 351±78 |
| 9.2±1.3 [4] | 111±16 | 166±24 | 221±31 | 277±39 | 333±47 |
| 10.4±1 [5] | 97±10 | 146±14 | 194±19 | 243±23 | 291±28 |

### *Implications for moment magnitude of rupture*

The elapsed time from the latest rupture of the northern Hayward fault is unknown. The latest event is believed to predate the Franciscan mission period, or ≤1776 AD (Toppozada and Borchardt, 1998). Time elapsed from the previous northern Hayward earthquake is thus ≥222 years. The rate determined here indicates that a future earthquake will produce a minimum displacement of 2.3 m (≥222yr * 10.4 mm/yr ≥ 2309mm ). From empirical data, a 30-50 km fault rupture, with this average displacement, would produce a moment magnitude in the range of 6.8 to 7.0 (Wells and Coppersmith, 1994).

Surface displacement of the Hayward fault is complicated by its high rate of creep, 5 mm/yr in the Berkeley area (Lienkaemper *et al.*, 1992). Despite the presumption that creep will reduce the magnitude of coseismic surface displacement by a factor of about 0.5, the fault is believed to be

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1 range of maximum displacement values from compilation of Wells and Coppersmith (1994)

2 Lienkaemper, J.J. and G. Borchardt (1996)

3 WGCEP (1990)

4 Lienkaemper, J.J. and G. Borchardt (1996)

entirely locked at depths greater than about 5 km, and to be accumulating potential slip at its full rate (WGCEP, 1990; Savage and Lisowski, 1993). Evaluation of the moment magnitude of a future Hayward earthquake is complicated by the fault's unusual slip behavior, and by revision of the length of the 1868 Hayward fault rupture by Yu and Segal (1996). Yu and Segal evaluated triangulation data spanning the 1868 earthquake and conclude that a best fit model for survey data favors a 50-55 km rupture length, with an average displacement of ~ 2 m. The Yu and Segal conclusions indicate that the 1868 Hayward fault rupture extended into north Oakland or even to Berkeley. This finding suggests that a northern Hayward rupture will probably be shorter than previously expected, perhaps extending from north Oakland to San Pablo Bay, with a rupture length of 30 to 50 km, depending on the rupture's overlap into the 1868 segment, and the length of fault rupture across San Pablo Bay (Yu and Segal, 1996; WGCEP 1990, Lienkaemper *et al.* 1991, Williams et al., 1998). Empirical data for strike-slip ruptures of 30 to 50 km indicate maximum surface displacements of 1.5 to 3 m (e.g. Wells and Coppersmith, 1994). These values indicate that the accumulated slip potential of ≥2.3 m is in the mid-range of expected maximum fault displacement for seismic rupture of the northern Hayward fault.

## Conclusions

The fault Hayward fault has displaced the present course of Strawberry Creek by 335 m (1100 ft). Prominent beheaded channels of Strawberry Creek are offset 580 m (1900 ft) and 730 m (2400 ft). The age of the younger paleochannel deposits, i.e. those associated with the 580-m-offset channel, is ≤32,200±360 radiocarbon years. This age marks the initiation of the modern (335 m) stream offset, and provides a direct record of the long-term-average slip rate of the Hayward fault, 10.4±1 mm/yr. This rate, if steady over a longer period, indicates that the older (730-m-offset) paleochannel was beheaded about 55,000 years ago. More accurate and robust forecasts of future Hayward fault rupture hazard are possible with this geologically-determined long-term slip rate. This significant increase in mean long-term rate, combined with recent documentation of a greater elapsed recurrence interval, produces a substantial increase in probabilistic rupture hazard. The new rate is slightly higher than that determined farther south along the fault from younger geological evidence, indicating general stability of slip rate distribution across Bay Area faults over a period of ≥30,000 years, hence essentially constant fault kinematics and geometry during this period.

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